DETECTION OF A SURFACE-BREAKING CRACK BY USING THE FREQUENCY ATTENUATION IN A LASER ULTRASONIC SPECTRUM

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Abstract

Laser ultrasonic system is a non-contact inspection device with a high spatial resolution and it is applicable to hard-to-access locations like in a nuclear power plant. In this paper, we have attempted to detect the depth of a surface-breaking crack by using the surface wave of a laser ultrasound. We have investigated a variation of the peak-to-valley value in the time domain and the spectrum distribution in the frequency domain according to the crack depth. The peak-to-valley value and high frequency coefficient are decreased in proportion to the crack depth. The high frequency attenuation is proportionally increased and the center-of-mass position of the frequency spectrum is proportionally lowered according to the crack depth.

In this paper, we describe the hardware configurations of the laser ultrasonic inspection system and the experimental results to detect a surface-breaking crack. We experimentally confirmed that the centroid variation of the frequency spectrum in the frequency domain provides better information about the crack depth than the amplitude variation of the ultrasonic signal in the time domain.

1. Introduction

Structural materials can be affected by various discontinuities that may have detrimental consequences on the integrity of a structure. These discontinuities could be produced during a fabrication or may result from degradation processes such as fatigue or stress corrosion cracks. Structural integrity and safety require the use of non-destructive testing(NDT) techniques to detect and characterize the discontinuities produced by these processes[1].

The characterization of surface defects is one of the key issues for industrial applications. There are many approaches to detect surface defects[2]. Ultrasonic testing(UT) is one of widely used for detecting, locating and sizing discontinuities in many industries.

One possibility to detect a surface-breaking crack is the use of ultrasonic surface waves[3]. Many theoretical and experimental studies using the Rayleigh surface waves, such as using the time-of-flight, amplitude variation, transmission and reflection coefficient, crack tip refraction etc., have been investigated in the time domain[3-6]. Also, many sizing techniques in the frequency domain, such as using the frequency attenuation, cut-off frequency variation, intercept frequency for the transmitted signals etc., have been studied[6,7]. Specially, recent advances in the field of non-contact ultrasonic testing has led to the possibility of using non-contact techniques, such as a laser generation[7,8], air coupled transducers or electro-magnetic acoustic transducers[5,6] to generate and detect Rayleigh waves.

A laser ultrasonic system is a non-contact inspection device which remotely generates ultrasound by using a pulse laser beam and it remotely measures the generated ultrasound by using a laser interferometer with a continuous wave(CW) laser beam. This system is better than conventional piezoelectric methods for the fundamental development of quantitative ultrasonic techniques. The laser ultrasound has a wide-band spectrum and it provides absolute measurements of a moving distance. Also, it can be applied to hard-to-access locations including curved or rough surfaces like in a nuclear power plant[1].

Several laser ultrasonic techniques are applied for the detection of micro cracks in a nuclear power plant[9,10]. Also, laser ultrasonic techniques are used to detect cracks in railroads and aircrafts[4,6,7]. A laser interferometer for an ultrasound detection is widely applicable though it is expensive and provides a low signal-to-noise ratio when compared to the conventional piezoelectric transducers.

One of the widely used measurement devices of an ultrasound is the Confocal Fabry-Perot Interferometer(CFPI) with a dynamic stabilizer. The dynamic stabilizer improves the stability of the CFPI by adaptively maintaining the optimum working status at the measuring time of the CFPI[11].

In this paper, we have carried out experiments to extract the depth information of a surface-breaking crack by observing the frequency attenuation of a laser ultrasound. Most of the energy of a surface wave exists within one-wave depth of its wavelength from the surface of an object. So, higher frequency components whose wavelength is shorter than the crack depth are decreased more in proportion to the crack depth. The center frequency value and centre position of each ultrasound spectrum are also decreased in proportion to the crack depth.

2. A configured laser ultrasonic inspection system

A fabricated laser ultrasonic system is shown in Fig. 1. We configured this inspection system on an optical table by using a pulse laser, a CFPI with a CW laser beam, a dynamic stabilizer and a computer.

The ultrasound is generated whenever a pulse laser beam is targeted onto the surface of an object. Then, the CFPI measures the surface displacement caused by the ultrasound at the target position of a CW laser beam. As we can see in Fig. 1, the linear polarized CW laser beam is focused onto the surface of an object after passing it through a half wave plate(HWP), a polarized beam splitter(PBS) and a focusing lens(L1). And then the backscattered light enters into the CFPI cavity after passing it through the L1, PBS and QWP. The ultrasonic signal will be detected after the laser beam is demodulated by the CFPI. The transmitted optical signal is converted to an electrical signal by an APD sensor D1. The high-speed A/D converter is synchronized by a targeting pulse laser beam which is captured by a photo sensor D2.

The computer digitizes the analog signals to the digital signals by using a high speed A/D converter. By virtue of the dynamic stabilizer, the computer captures the ultrasound at the maximum gain time of the CFPI whose gain is periodically varied. The computer processes the ultrasonic signal in a real time to extract the depth information of a surface-breaking crack.

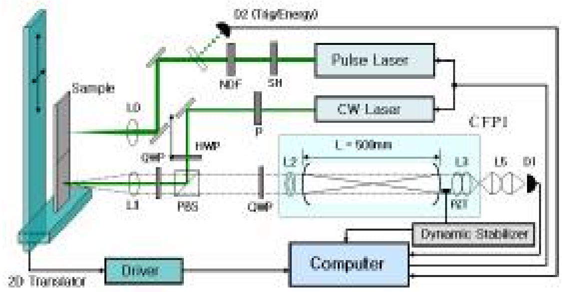


Fig. 1 The configuration of a configured laser ultrasonic inspection system

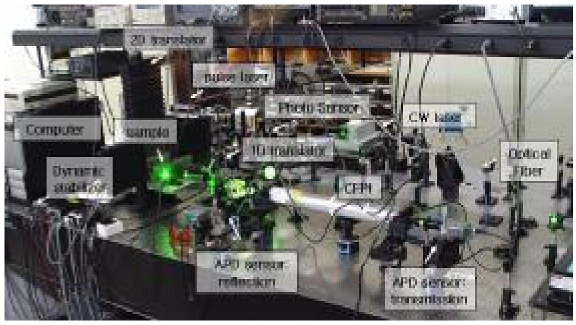


Fig. 2 The photograph of a configured laser ultrasonic system

A photograph of the configured experimental system on an optical table is shown in Fig. 2.

For a control and signal processing, we used a personal computer equipped with a high-speed data acquisition board(AL81G, ALI Inc.) and a multifunction board (PCI9112, ADLink). Also, we used a pulse laser(Quantel-Brilliant) to generate ultrasound and a CFPI(CFT-500, Buleigh, FSR 150MHz) using a stabilized CW green laser to remotely measure the ultrasound. The computer controls a 2-D translator(ATS212-M, Aerotech Inc) through Ethernet communications by using a LAN port. We built a high-speed and high-gain Avalanche Photo Detector(APD : C3090E, PerkingElmer) to acquire the transmitted ultrasonic signal of the CFPI. The optimum period of the pulse laser is 10 Hz and the full-width at the half-maximum(FWHM) of a pulse laser beam is about 10 ns. A pulse laser beam is on- or off-controlled by a shutter(SH) and its power is controlled by a neutral density filter(NDF).

3. Experiments for the depth measurement of a surface-breaking crack by using the laser surface wave

We artificially designed two crack samples on stainless steel 316 for the experiments. The crack depths are no crack, 100µm, 200µm, 300µm and 500µm on the 1st sample. On the 2nd sample, the crack depths are continually varied from 10µm to 100µm. We used a line-shaped pulse laser beam with a length of 7 mm to generate ultrasound with a strong directivity. The energy of a pulse laser beam is about 40 mJ and 30mJ for the 1st and 2nd samples respectively. We used a stabilized CW laser beam to measure the laser ultrasound. The energy of the CW laser beam is about 120mW and 80 mW for the 1st and 2nd samples respectively. The experimental set-up to detect the crack depth information of a surface-breaking crack is shown in Fig. 3.

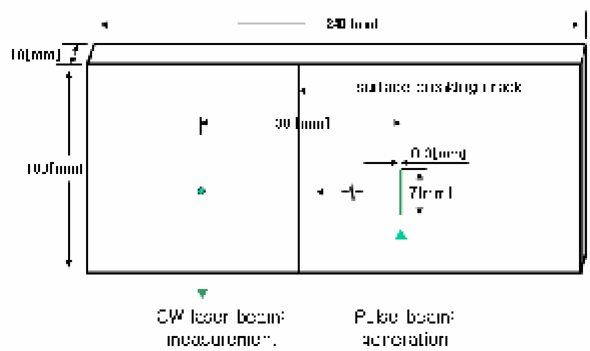
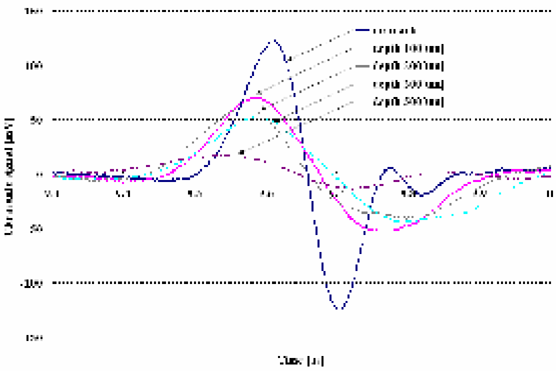


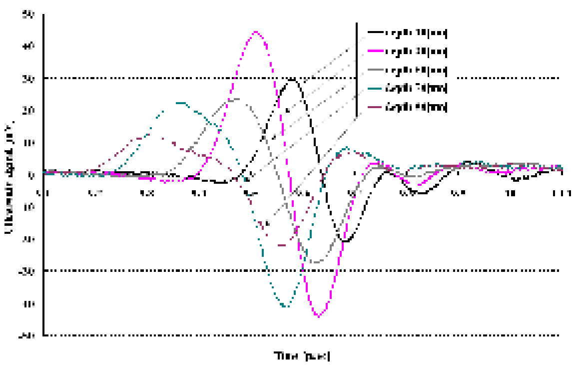
Fig. 3 Experimental set-up to detect a surface-breaking crack.

The CFPI measures the transmitted ultrasound for a surface-breaking crack. The acquired ultrasound by using the CFPI is the differential value for a surface movement. The distance between the pulse laser beam and the measuring laser beam is about 30 mm. A surface-breaking crack is positioned in the middle of the two laser beams.

The measured surface waves of the laser ultrasound in the time domain according to the depth of the surface-breaking cracks are shown in Fig. 4. Transmitted signals from the crack depth of 100µm to 500µm and from 10µm to 90µm are shown in Fig. 4(a) and Fig. 4(b) respectively. Here, each signal is an averaged signal from 40 ultrasound signals for each crack. As we can see in Fig. 4, the amplitude is proportionally decreased according to the depth of a surface-break crack. Also, we can see that the high frequency components of the signals are decreased because the time period of the ultrasonic signal is proportionally elongated according to the depth of a crack.



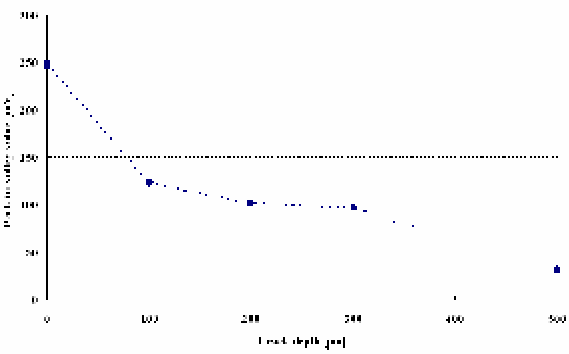
(a) Crack depth from 100µm to 500µm



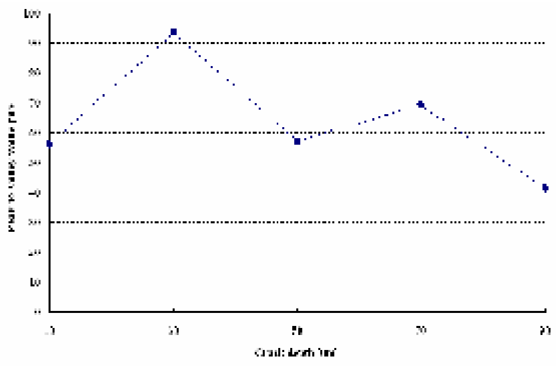
(b) Crack depth from 10µm to 90µm

Fig. 4 Measured surface waves of laser ultrasound according to the depths of surface-breaking cracks in the time domain.

The peak-to-valley values in the time domain according to the depths of no crack, 100µm, 200µm, 300µm and 500µm of Fig. 4(a) are shown in Fig. 5(a). Also, the peak-to-valley values according to the crack depth of no crack, 10µm, 30µm, 50µm, 70µm and 90µm of Fig. 4(b) are shown in Fig. 5(b). Here, though the amplitude of the laser ultrasound is proportionally decreased according to the deep crack depth like in Fig. 5(a), but we can not discriminate the crack depths by observing the amplitude variation when the crack depth is small like in Fig. 5(b).



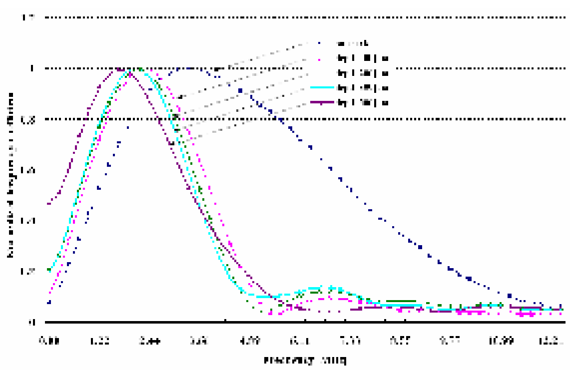
(a) Crack depth from 100µm to 500µm



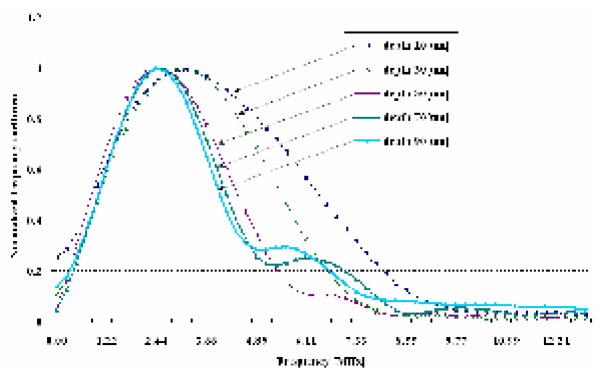
(b) Crack depth from 10μm to 90μm

Fig. 5 Averaged peak-to-valley values according to the crack depths

The spectrum patterns of the ultrasonic signals in Fig. 4(a) and Fig. 4(b) are shown in Fig. 6(a) and Fig. 6(b) respectively. We can see that the high frequency components are proportionally decreased according to the crack depths. Also, the center frequency value is proportionally decreased according to the crack depths.

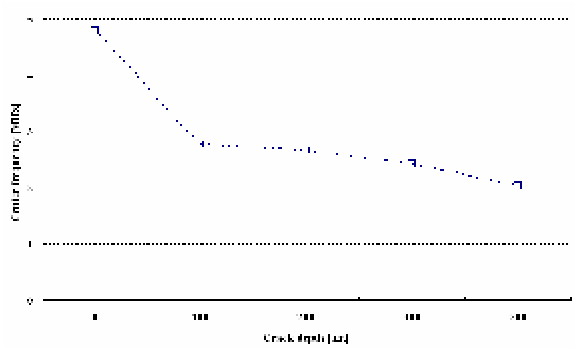


(a) Crack depth from 100μm to 500μm

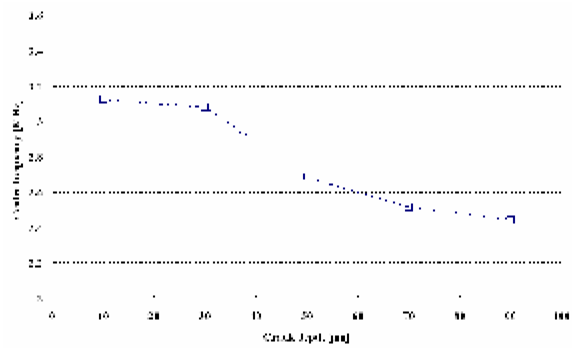


(b) Crack depth from 10μm to 90μm

Fig. 6 Spectrum distributions of the laser-generated surface waves according to the crack depths



(a) Crack depth from 100μm to 500μm



(b) Crack depth from 10μm to 90μm

Fig. 7 The averaged value of the center-of-mass frequency position according to the crack depths

The extracted center-of-mass positions of the ultrasound spectrums in the frequency domain in Fig. 6(a) and Fig. 6(b) are shown in Fig. 7(a) and Fig. 7(b) respectively. The higher frequency components are considerably decreased in proportion to a deeper crack depth. Also, the center frequency value of each ultrasound spectrum is decreased in proportion to the crack depth. We can clearly see that the center-of-mass value of frequency distribution and high frequency components are proportionally decreased according to the crack depth. When we compared the experimental results between Fig. 5 and Fig. 7, the observation method of the center frequency in the frequency domain is more efficient than that of the peak-to-valley value in the time domain for measuring the depth information of a surface-breaking crack.

Equation (1) shows the transfer function for a surface-breaking crack.

$$p(t) = \sum_{m=1}^{1024} g(m) i(t-m) \qquad (1)$$

Here, the notation i is the originally generated ultrasonic signal and p is the transmitted ultrasonic signal for a surface-breaking crack in the time domain. The function g is the transfer function for a surface-breaking crack.

We extracted the transfer function in the frequency domain according to equation (2) because it is very complicated to calculate the transfer function in the time domain.

$$G(s) = \frac{P(s)}{I(s)} \qquad (2)$$

Here the notation I, P and G are corresponding signals in the frequency domain for the functions i, p and g of equation (1).

The extracted and normalized transfer functions from no-crack to the crack-depth of 500μm are shown in Fig. 8. As shown in Fig. 8, no frequency attenuation is shown for a no-crack sample and the high frequency attenuation is increased in proportion to the crack depth.

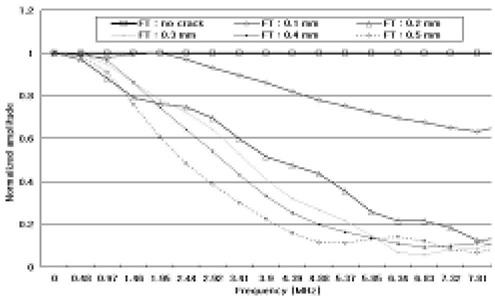


Fig.8 Fourier transformed transfer functions according to the crack depths of the surface-breaking cracks

Depth information usually can be extracted by looking at changes in the signal amplitude and frequency content. For signals with a wavelength longer than the crack depth, a larger fraction of the surface wave energy will be able to pass under the crack. But, for signals with wavelengths shorter than the crack depth, the surface wave energy will be effectively blocked by the crack.

A surface-breaking crack acts like a kind of a low pass filter for the ultrasonic surface wave because most of the energy of a propagating surface wave exists within one-wave depth of its wavelength from the surface. So, the value of the cut-off frequency is decreased in proportion to the crack depth.

In this paper, we extracted the crack depth information by using the frequency attenuation. The extracted crack depth information by using the attenuation for a specific frequency value of 2.93 MHz is shown in Fig. 9. Here, we can see that the attenuation of a specific frequency is decreased in proportion to the crack depth.

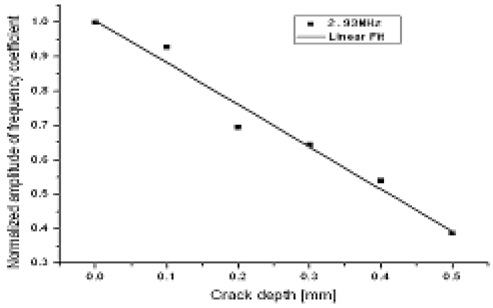


Fig.9 Normalized amplitude of the frequency coefficient of 2.94 MHz according to the crack depths

The extracted crack depth information by using the averaged frequency attenuation from 1.95MHz to 5.37 MHz is shown in Fig. 10. The averaged frequency attenuation of a certain range of the frequencies is decreased in proportion to the crack depth. Here, the solid line in Fig. 9 and Fig. 10 is a fitted line.

From the crack depth measuring experiments using a laser surface wave, we can see that the amplitude of a transmitted surface wave is decreased and the high frequency attenuation of a transmitted surface wave is increased in proportion to the crack depth. The energy loss is increased when the frequency is higher. Also, the high frequency attenuation in a transfer function for a surface-breaking crack is increased according to the crack depth. The center position of a frequency spectrum is also lowered according to the crack depth.

We confirmed through experiments that the frequency analysis method provides better crack depth information than the amplitude analysis method.

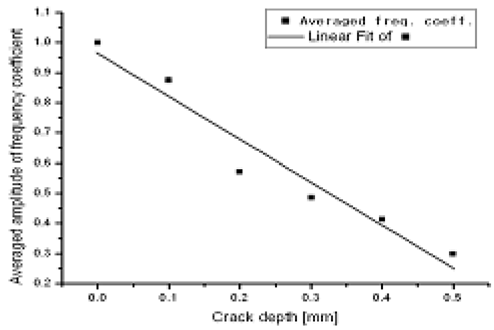


Fig.10 Averaged amplitude of the frequency coefficient from 1.95 MHz to 5.37 MHz according to crack depths

4. Conclusions

We have carried out experiments for the detection of the depth of a surface-breaking crack by using a laser surface wave with a wide-band spectrum. We configured a laser ultrasonic inspection system by using a pulse laser and a CFPI with a CW laser on an optical table for the experiments.

Through the experimental results, we confirmed that the high frequency attenuation and the center-of-mass position of a spectrum provide better crack depth information than the amplitude variation. Also, the high frequency attenuation of the transfer function for a surface-breaking crack provides reliable crack depth information.

5. References

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